BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B69 11007

SUBJECT: Assessment of Expendable Tankage for Low Cost Transportation Systems Case 105-3

DATE: November 5, 1969

FROM: A. S. Kiersarsky

ABSTRACT

This memorandum discusses various factors which affect cost of expendable tankage for low cost transportation systems. Production quantity and rate, program planning, design and fabrication, and tank transportation are among the factors discussed.

The initial planning phase exerts considerable influence on cost since it establishes a system traffic pattern which in turn sets production rate and quantity. Both of these factors must be relatively high to achieve low tank costs and this is demonstrated by comparisons with other aircraft and launch vehicle structures.

Tankage design type is also an important factor since it has a direct influence on the fabrication methods and facilities. This is illustrated by a discussion of manufacturing operations for dome type tank ends and a comparison of Atlas and Thor tankage.

Materials and tank transportation costs are found to make only minor contributions to tankage cost but become more important as low overall tankage cost is approached.

N79-72194

(NASA-CR-107139) ASSESSMENT OF EXPENDABLE TANKAGE FOR LOW COST TRANSPORTATION SYSTEMS (Bellcomm, Inc.) 30 p

Unclas
00/16 11656

FF No. 60 CR-107139 (NASA CR OR TMX OR AD NUMBER) (CATEGORY)

BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B69 11007

SUBJECT: Assessment of Expendable Tankage for Low Cost Transportation Systems - Case 105-3

DATE: November 5, 1969

FROM: A. S. Kiersarsky

MEMORANDUM FOR FILE

1.0 INTRODUCTION

The space program during the past decade has been using expendable systems for launching space payloads. Until now, other than for military purposes, the launch rates have been relatively low, but projected plans for the future indicate a more active program with flights possibly increasing by an order of magnitude or greater. This planned increase will undoubtedly demand a more economical launch approach.

To achieve this goal, studies of different concepts are being conducted; namely, a partially reusable system, a fully reusable system, and a cost optimized expendable launch system. The objective of these studies is reduction of cost by recovery and reuse of launch systems, or an across the board cost reduction of expendable launch systems. Examples of recent design concepts studied include:

Partially reusable ILRV* (References 1, 2, 3)
- Star Clipper** (expendable tankage)

Expendable Systems
- Cost Optimized Launch Vehicle (COLV, Reference 4)

Fully Reusable ILRV
- Triamese (Reference 5)

This memo is addressed to the first two concepts which expend propellant tankage. Tankage for the partially reusable ILRV is a significant portion of the vehicle operation costs (cost per flight). For the COLV, tankage is a smaller percentage of operation cost but is still considered a prime area for cost reduction.

---

*Integrated Launch and Reentry Vehicle

**The partially reusable concept has recently been dropped from the NASA Space Shuttle studies, but some Air Force sponsored studies are continuing.

The following factors were examined to provide some understanding of what influence they may have on cost.

- Production Quantity
- Production Rate
- Program Planning
- Design and Fabrication
- Transportation

For comparison purposes, other production units were examined such as the automobile, aircraft tip tanks, military and commercial aircraft, and present launch vehicle propellant tankage.

2.0 PRODUCTION QUANTITY

The cost per pound of manufactured products tends to decline as additional units are manufactured. This phenomenon is referred to as the "learning curve" effect. This "learning" is a result of labor and material saving experiences gained during manufacturing operations and the introduction of tooling and other machinery for mass production. The basic content of this theory is that each time the total quantity of items produced doubles, the cost per item is reduced by a percentage of its previous value. This method of predicting cost for production units has been commonly used in the aircraft industry and is applied to costing of low cost tankage. An estimate of how the quantity of units can affect tank cost is given in Figure 1 which applied to Lockheed's ILRV concept (1).

3.0 PRODUCTION RATE

In addition to and related to production quantity, production rate has a significant effect on unit cost. This is a result of several factors namely 1) spreading company overhead over a larger number of units, 2) more efficient utilization of personnel by eliminating slack time between production units, and 3) use of mass production tooling and machinery. For example, the Saturn V SIC stage is currently produced at a rate of two per year. This rate is inefficient since the use of skilled labor has been intermittent and not continuous (4). This results in problems of personnel placement when operations are separated as a result of low production rate. Also, each time personnel return to their particular operation a reorientation or learning cycle is repeated.

The current production rate for some present launch vehicles has been relatively small--approximately 10 units per year for Thor, Atlas, and the Titan family. Table 1, shows normalized cost (6) as a function of production rate for two of the above launch vehicles (less engines).

Non-space hardware also illustrates the effects of production rate on cost. To better appreciate this, a review of several types of different hardware was made:

- Automobiles - Present production cost for the so-called big three is approximately $1.00 per pound for a unit production rate of one per minute (this price is for a complete auto, not just structure).

- Aircraft Tip Tanks - These units are produced at the rate of 50-55 per day for a cost of $11.00 per pound (7) (this unit is an accessory used on the F-4 aircraft).

- Military Aircraft (F-4) - This is a complex structure which uses a variety of fabrication methods as well as diversity of materials and costs approximately $30.00* per pound based on a production rate of 2-3 per day.

These are just a few examples of non-space hardware for comparison of production rate and cost. Table 2 presents a more comprehensive view of this factor for the above units and other hardware along with low cost tankage.

4.0 PROGRAM PLANNING

The planning function was reviewed to determine if any decisions which are made during this phase could affect tankage economics. Of particular interest is the determination of a viable traffic pattern (i.e., usage or production rate) since costing of tankage is based on rate as well as quantity factors. To illustrate this, a comparison of production rate versus years was made for various contracted quantities (Figure 2). As shown, depending on the usage rate, the span can vary from approximately one year at a rate of 4 per month to four years at a rate of 1 per month for a 50 unit program. If the contract increased to 200 units the span could vary from four years for a rate of 4 per month to approximately 17 years for a rate of one per month. A significant observation can be made at this point. The achievement of low cost tankage will require both a high production rate and a high production quantity. For example, at a low

---

*Approximate cost quoted by McDonnell personnel at meeting on November 13, 1968, McDonnell Douglas, St. Louis, Missouri.

production rate (say one per month) the projected low tank cost indicated in Figure 1 (at the 200th unit) would only be achieved after 17 years. This is probably well beyond the useful lifetime of any reusable ILRV or COLV concept! Therefore, the projected traffic pattern or program plan will influence estimated tank costs.

5.0 TYPICAL CONFIGURATIONS

Two concepts for ILRV drop tankage are shown in Figures 3 and 4, namely individually attached tank units and an integral tank arrangement in the form of an inverted "vee" within which the spacecraft is supported. For this study no attempt is made to assess the differences between these concepts but only to review some detail design features and determine how these features and their associated fabrication methods may influence cost. A description of the COLV expendable tankage is also given.

5.1 Drop Tankage

The McDonnell tip tank concept (Figures 3 and 5) is a statically stable structure for both the propellant tankage and thrust attach structure. It is composed of two basic units, the LH_2 tank and LO_2 tank spliced by ring frames on both units. The LH_2 tank is a combination of monocoque and integrally stiffened (7039 aluminum) structure. It is composed of a gore segmented concave bulkhead at the upper end to which is spliced the cylindrical tank section. The splice member also functions as the intertank splice ring. The tank is enclosed at the lower end by a spherical convex bulkhead which is spliced to the cylindrical section at the lower end by the tank to spacecraft splice ring. The LO_2 tank is also a combination of monocoque and integrally stiffened (7039 aluminum) structure. It is composed of a truncated cone forward section, an inter-tank splice ring, and a spherical bulkhead. The nose cap is a spun stainless steel structure. The primary assembly method of fabrication for this tankage is fusion welding.

The Lockheed tip tank concept, Figure 6, is a combination of pressure stabilized structure for the propellant tankage and statically stable structure for the inter-tank and thrust structures. The primary method of fabrication for this

tankage, except for the LO_2 tank, is the "glue weld"* technique (1, 2). This tankage consists of five basic elements: a nose cone, a LO_2 tank formed of two mirror reflected sections and two cylindrically shaped LH_2 tanks. The nose cone used only for fairing, consists of a stainless steel monocoque shell cap and a 2219 aluminum cone frustrum afterbody which has integrally stiffened structure. The LO_2 tank (2219 aluminum) consists of two intersecting cylindrical sections with hemi-spherical ends forming the pressure closing bulkheads. These two assemblies are joined by a tension splice at the plane of intersection along the centerline. At each end of the LO_2 tank is a 2219 aluminum interstage structure to which the nose cone and LH_2 tanks are spliced. The primary structure of the LO_2 tank is ring stabilized monocoque structure using the resistance weld method** of assembly. The LH_2 tank (also 2219 aluminum) consists of a ring stabilized monocoque cylindrical section with a gore segmented hemispherical dome forming the pressure bulkhead at the forward end and an integrally stiffened truncated structure at the aft end which is part of the drop tank to spacecraft splice structure.

5.2 COLV Tankage

Another design concept reviewed was the "Cost Optimized Launch Vehicle" (COLV) which is completely expendable. The feasibility of this approach relies on the use of low cost components and vehicle structure. To attain this goal for the structure, both the propellant tankage and interstage structure are designed to use low cost material and commercial fabrication techniques.

This concept (Figure 7) is a multi-stage design using statically stable structure. Each stage is fabricated from HY-140 high strength steel. The tankage as well as the interstage structure are monocoque structure joined by fusion welding. (This selection imposes a weight penalty since material gauges must be substantially increased.) No weld lands

---

*The glue weld method of assembly is a combination of the resistance method of welding and a high strength aluminum filled epoxy.

**The glue weld method employed in the LH_2 tank and elsewhere is not compatible with LO_2.

are required. Elimination of weld lands and use of statically stable monocoque structure leads to significant cost reductions. It is estimated that such a design would result in tankage costs of $2.50 per pound for lower stages and $16.00 per pound for upper stages. Upper stages would be more expensive due to the closer tolerances required and the greater number of parts per unit tank weight.

As previously noted, one goal was to fabricate this tankage by using commercial fabrication techniques. This has been demonstrated* by fabrication of a scaled down experimental stage 8 1/2 feet in diameter and approximately 45 feet long (Figure 8). Presently, this appears to be the only test article fabricated to evaluate the feasibility of low cost booster tankage. A limiting feature for tankage using HY-140 steel is the operating temperature range. This range, shown in Table 3, precludes the use of cryogenic propellants.

6.0 DESIGN AND FABRICATION

Selected methods of fabrication were studied to explore differences which may impact on cost.

6.1 Fabrication Comparison (Example)

The various steps and operations required for fabrication of a dome, which is a typical part of tankage structure, was selected for review. In Figure 9 a comparison was made of different dome designs, namely, a weight optimized fusion welded assembly, a cost optimized fusion welded assembly, and a resistance welded assembly. Each of these designs require certain basic manufacturing operations, but the weight optimized fusion welded design requires considerably more operations; particularly those for material removal (i.e., chem-milling).

Chem-milling is a multi-stepped operation with parts cycling through cleaning, masking, etching, and rinsing operations. Each of these operations require special handling to avoid part contamination. Also, this fabrication method is unique requiring a separate facility. It therefore becomes apparent that weight reduction imposes a significant cost factor, since the requirement for material removal involves many and varied manufacturing operations.

---

*Both Boeing and Dixie Mfg., a commercial tank fabricator, have constructed tanks at comparable low costs.

The cost optimized fusion welded assembly is used on the (COLV) whereas the weight optimized assembly is current practice on existing launch vehicles. The resistance welded assembly, which is comparable to the cost optimized assembly, is only suitable for thin gauge tankage. It is used in the Atlas and also for fabrication of tankage in one ILRV concept.

6.2 Joining

There are numerous ways of joining structures for pressurized propellant tankage and each of these has associated advantages and disadvantages. Joining methods have been based primarily on the type of tankage structure which is either statically stable or pressure stabilized. As noted, pressure stabilized structures* are typically thin gauge and this permits the relatively simple technique of resistance welding. The resistance weld method of assembly was used for Atlas and Centaur vehicles (both of which were pressure stabilized structures). Fusion welding has been the principal method for tankage assembly of most all other launch vehicles designed with integrally stiffened statically stable structure. Also, this method in contrast to resistance welding requires more complex fixtures to maintain positional tolerances at the weld. Some of the features of various types of tankage component joining are shown in Table 4.

One design requirement which has had an effect on tankage fabrication is the "weld land" used at joints of propellant tank sections using fusion welding. Use of this edge design has had a marked impact on the manufacturing operations required for material removal outside of the land area. This material is removed by chem-milling (as previously discussed for dome elements) or by machining. These operations are costly.

Design of a weld land is also significant since many design and fabrication factors are involved. To better appreciate these factors a typical weld land and its associated requirements (8) are shown in Figure 10.

---

*A drawback of pressure stabilized vehicles is the requirement of constant pressurization to maintain structural shape. This necessitates equipment to measure differential pressures and internal pressure of the tankage.

6.3 Fabrication Complexity

The degree of fabrication complexity for different types of structures was also examined as a measure for cost comparison. It is difficult to make a quantitative comparison between structural configurations, since different fabrication processes and equipment are involved. However, to provide some basis for comparison, a complexity index (10) was established. Establishment of this index was based on historical data of various contractors for past and on-going programs. Some indication of the degree of complexity (9)(10) for different types of structure is shown in Table 5.

If low cost tankage structure were fabricated using a single form of construction consisting entirely of a single material the above factors would apply, but in reality these vehicles are composed of different materials using various types of construction. Therefore some average of these factors applies.

To determine how and to what degree complexity may influence cost, a comparison was made of the Atlas and Thor launch vehicle tankage.

6.3.1 Atlas-Thor Comparison

The Atlas tankage is constructed of a thin wall fully monocoque structure. Rigidity is derived by internal pressurization. This tankage consists of a cylindrically shaped section with different end attachments. A truncated conical section at the upper end forms part of the external shape. The tankage ends are closed by a gore segmented dome at the upper end and a conical structure for the lower closure. The oxidizer and propellant tankage are separated by a common wall domed shaped bulkhead. There is no intertank structure. This tankage is fabricated from 301 stainless steel material using the resistance weld method for tankage assembly.

The Thor is self supporting and designed to permit handling without propellant tank pressurization. This vehicle is configured with separate propellant tankage joined by an intertank structure. The external shape is similar to Atlas in that the lower part is cylindrical and a truncated section forms the upper section of the tankage. The tankage utilizes a waffle pattern design machined into the inside surface for strength. These tank skins are machined from aluminum plate to the cylindrical shape. The tank bulkheads are weight optimized domed shaped gore segmented assemblies. The intertank structure consists of skin, stringers and frames. This tankage and intertank structure is fabricated from 2014 aluminum using the fusion weld method of assembly with weld lands as required.

The basic designs of the vehicles are different; one uses pressure stabilized structure and the other uses statically stable structure. With each of these design concepts the material selection and method of fabrication was also quite different. This complexity difference correlates with the differences in cost. The Thor has a complexity factor somewhere between 1.8 and 2.2 with a cost of $41.00 per pound whereas the Atlas has a complexity factor of 1.5 with a cost of $27.00 per pound.

6.4 Materials

Sheet material forms the major part of tankage structure and can influence cost. As previously noted the ILRV concepts use weldable aluminum alloys. As shown in Table 3 the procured cost for these alloys ranges from approximately $1.00 per pound for 2219 aluminum to $2.50 per pound for the 7039 aluminum. By comparison these raw materials form a relatively small part of the estimated overall cost per pound of tankage.* To illustrate this, the material cost with respect to the delivered cost per pound was compared for different production quantities of the Lockheed ILRV concept (Figure 1).

- For the 200th unit produced at the delivered price of $29.00 per pound the material cost factor is approximately 3 1/2%.

- For the 50th unit produced at the delivered price of $48.00 per pound the material cost factor is approximately 2%.

Therefore materials are a small cost relative to total fabricated cost. Of course as the production quantity increases and the per pound cost goes down, the material cost does become more important. Material selection, then, is more important for reasons of ease of fabrication and favorable properties rather than cost.

7.0 TRANSPORTATION

As launch vehicle tankage increases in size, the modes of transportation between factory and launch sites become more limited.

---

*This assumes that only a small amount of material is wasted by machining operations as would be the case if final sheet thickness does not differ significantly from the as rolled condition.

Today one of the largest cargo aircraft is the C5A. The cargo compartment (11) for this aircraft, Figure 11, has a maximum height of 13.5 feet. This dimensional envelope limits the transport of cylindrical type containers to 12.5 feet or less since tankage support will consume some part of this 13.5 feet height. Earlier aircraft, such as the C124 and C133, constrained the Atlas and Titan tank diameter to 10 feet.

The highway system also limits the tankage size to less than 13 feet since bridge clearances on federally financed highways are designed with a clearance of 13' 10". Railroads, the other land based mode of transport, were not studied but discussions indicated that 13' dia. is also a limiting factor. Therefore for ILRV tankage diameters in excess of 12-13 feet, transportation will be limited to water transportation or the Super Guppy aircraft (presently used for transporting the SIVB stage). If location of launch sites are such that only air transport is feasible then more aircraft of super guppy type or possibly a new aircraft designed specifically for this purpose may be required.

The super guppy is contracted for by NASA based on utilization and mileage. The fee, presently charged NASA for use of the aircraft is approximately $10.00 per airline mile.* Assuming 3000-6000 airline miles (which includes delivery of tankage to launch site and return of empty aircraft to factory) and approximately 30,000 lbs. of tankage, it is estimated that transportation adds the order of $1-2 per pound to tank cost.

8.0 SUMMARY AND OBSERVATIONS

The preceding study has briefly reviewed some factors which influence cost for space shuttle expendable tankage. Even though expendable tankage was used for purposes of exploring costs most of the areas studied also applies to other space program hardware.

Some points of interest and observations from this study are noted:

- The initial planning phase as formulated by the procuring agency will have a definite influence on cost since this early phase will determine the total quantity of units and the production rate. As stated, low cost tankage will require both a high production quantity and production rate.

---

*This cost was provided by the airlift management sections of the Transport and Logistics Division of NASA.

- Production rate has a direct influence on the effectiveness of the company labor force. For a higher rate of production this force is used more effectively and the cost per unit will decrease. At lower production rates this force is rotated on and off a project. This reduces effectiveness since personnel retraining or relearning is required.

- High production quantity can reduce unit costs due to the learning curve effect and the introduction of labor and material saving aids.

- Fabrication methods and facility requirements are largely influenced by the basic design selection. For weight optimized designs, significant costs are due to the requirements for joining (welding) and material removal which involve many and varied manufacturing operations. For a "cost optimized design" where a weight penalty is considered a design variable, these operations are held to a minimum.

- Raw materials appear to be a small part of unit cost, and affect cost primarily to the extent that they permit simpler fabrication methods.

- Assuming high production rate and production quantity and minimal fabrication complexity, the cost per pound data for Thor and Atlas tankage and F-4 structure suggest that expendable ILRV tankage can be fabricated for less than $40.00 per pound.

- Transportation of IRLV tankage appears to be only a minor component of total tank cost.

A. S. Kiersarsky

1013- ASK - kle

Attachment
References

REFERENCES

1. Proposal for Analytical Investigation of Low Cost Expendable Fuel Tanks for Advanced Staging Vehicle Concepts, LMSC A 941109 Volume I, Technical and Management Proposal, December 2, 1968, Lockheed Missile and Space Division, Sunnyvale, California, CONFIDENTIAL.

2. Space Shuttle Drop Tank Description, LMSC A 951762, June 25, 1969, Lockheed Missile and Space Division, Sunnyvale, California.

3. Integral Launch and Reentry Vehicle Presentation Brochure, Received from McDonnell Douglas, St. Louis, Missouri, by D. E. Cassidy and C. C. Ong.

4. Kiersarsky, A. S. "Review of the Design and Fabrication of a Low Cost Expendable Launch Vehicle," Bellcomm Memorandum for File, May 6, 1969.

5. Orbital Transport Concepts: Report No. GDC-DC B69-003, January 29-30, 1969, General Dynamics, Convair Division, San Diego, California.

6. Kiersarsky, A. S. "Cost Data Investigation of Booster System Propellant Tankage," Letter to H. S. London, April 10, 1969.

7. Kiersarsky, A. S. "Discussion of F-4 Tip Tank Fabrication," Bellcomm Memorandum fcr File, March 20, 1969.

8. Brubaker, W. C., Private Communication and Personal Notes.

9. Launch Vehicle Component Costs Study, Technical Report Volume II, Contract No. NAS 8-11368, June 30, 1965, Lockheed Missile and Space Company.

10. Design Considerations of Reusable Launch Vehicles - Final Report, Volume V, Launch Vehicle Cost Program Book 1, Cost Program Formulation, Douglas Report DAC 57916, October, 1966, Douglas Aircraft Co., Inc., Santa Monica, California.

11. Wilcox, A. N. and Monti, J. H."C-5 Troop/Cargo Handling Subsystems," Lockheed Georgia Co., Division Lockheed Aircraft Corp.

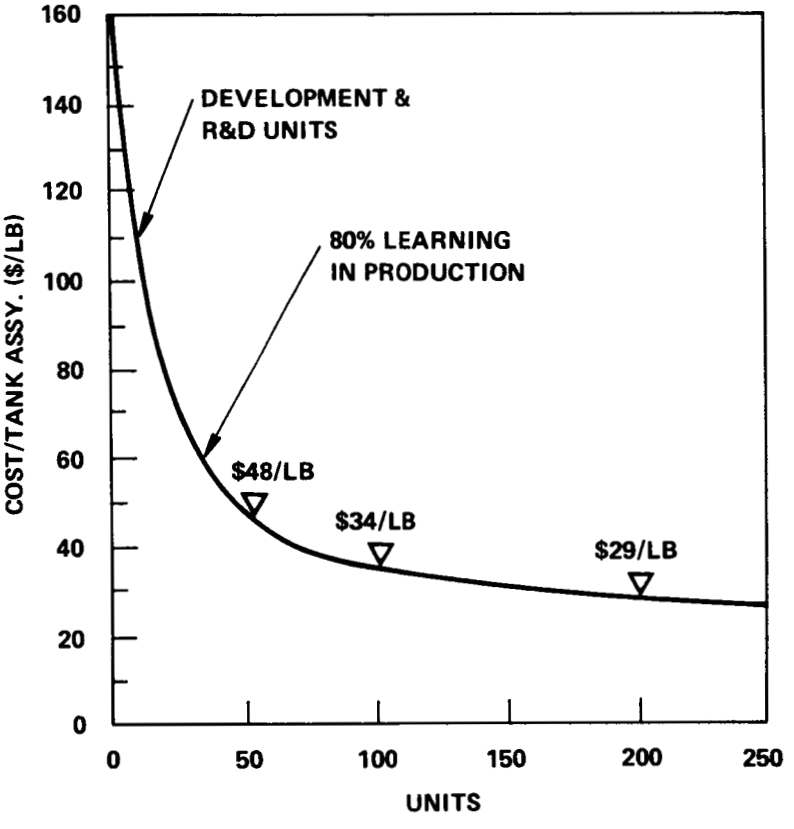


FIGURE 1. DROP TANKAGE COST PROJECTION (LOCKHEED)

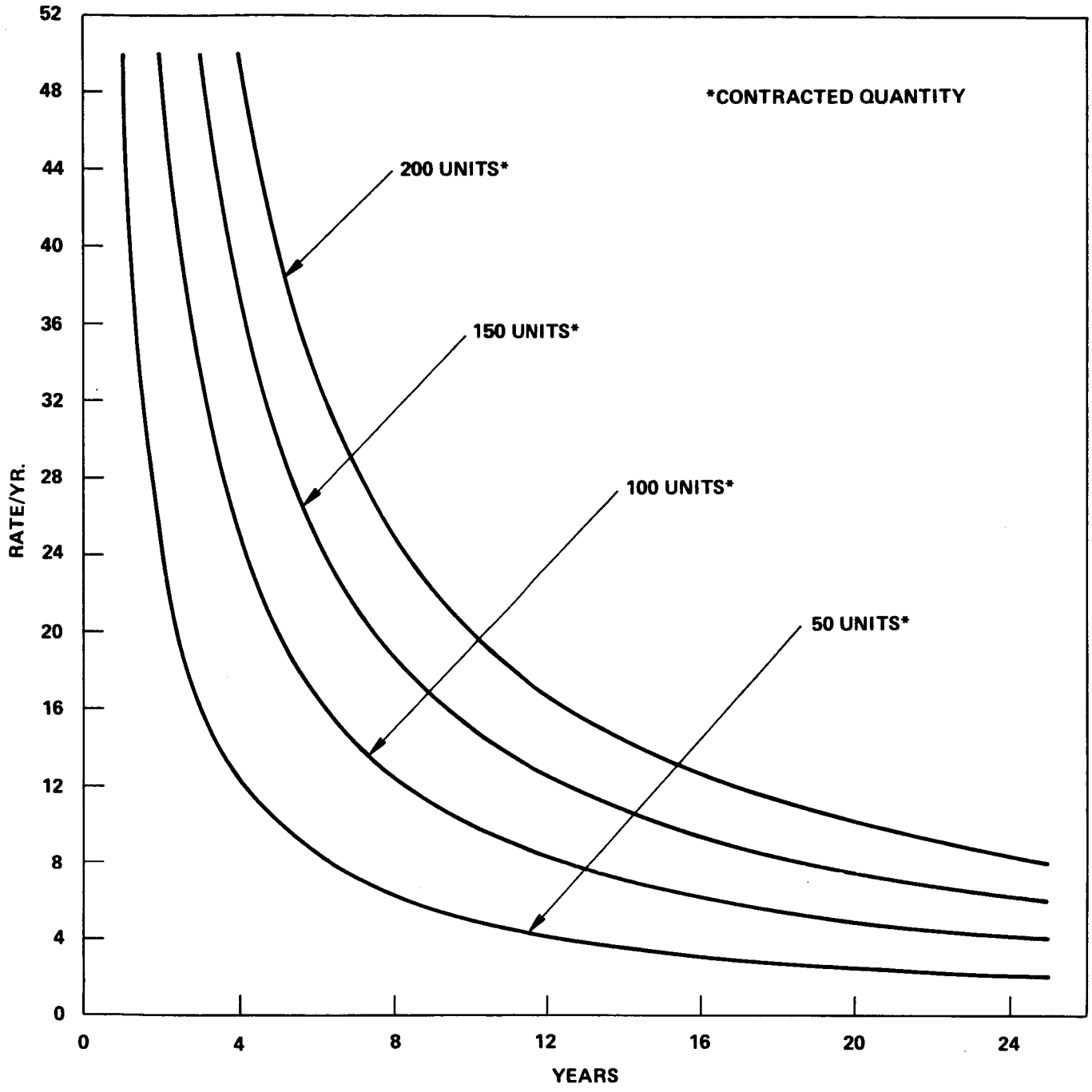


FIGURE 2. PRODUCTION RATE VS. YEARS

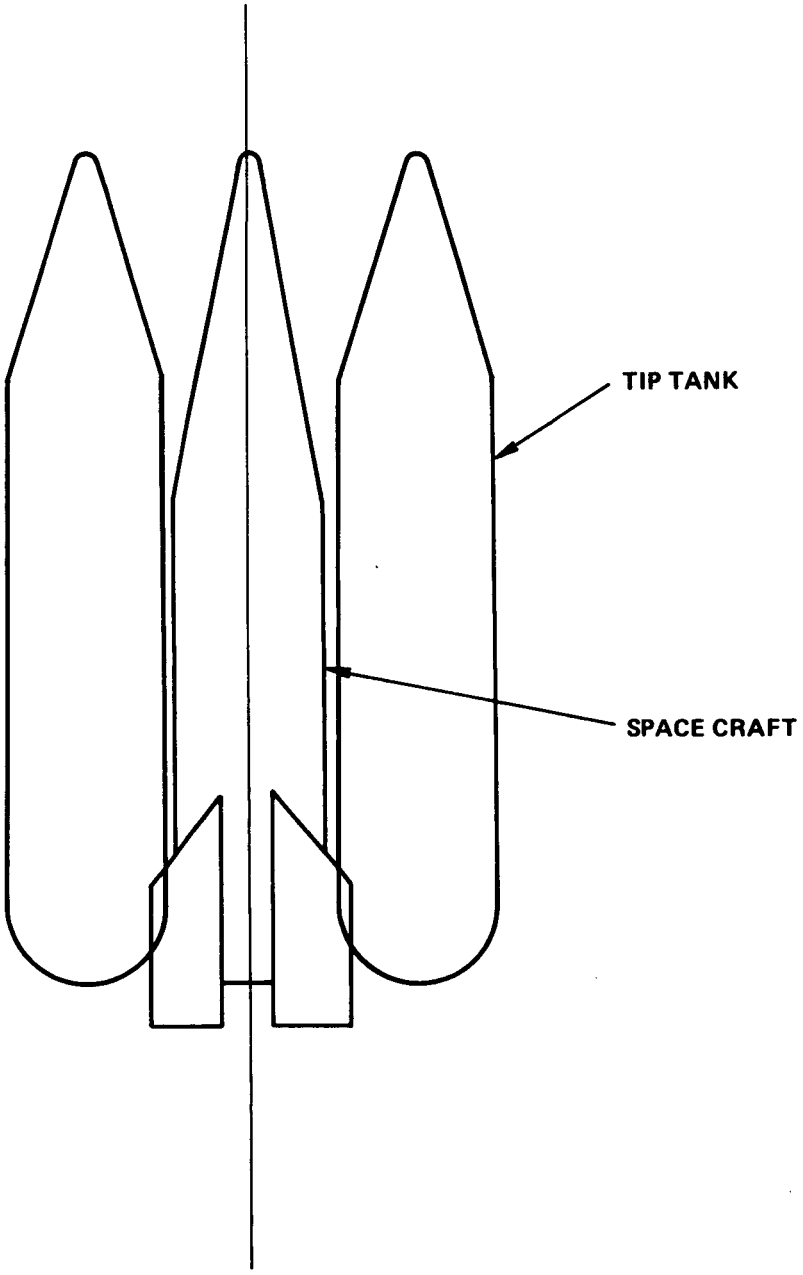


FIGURE 3. McDONNELL DOUGLAS TIPTANK (ILRV)

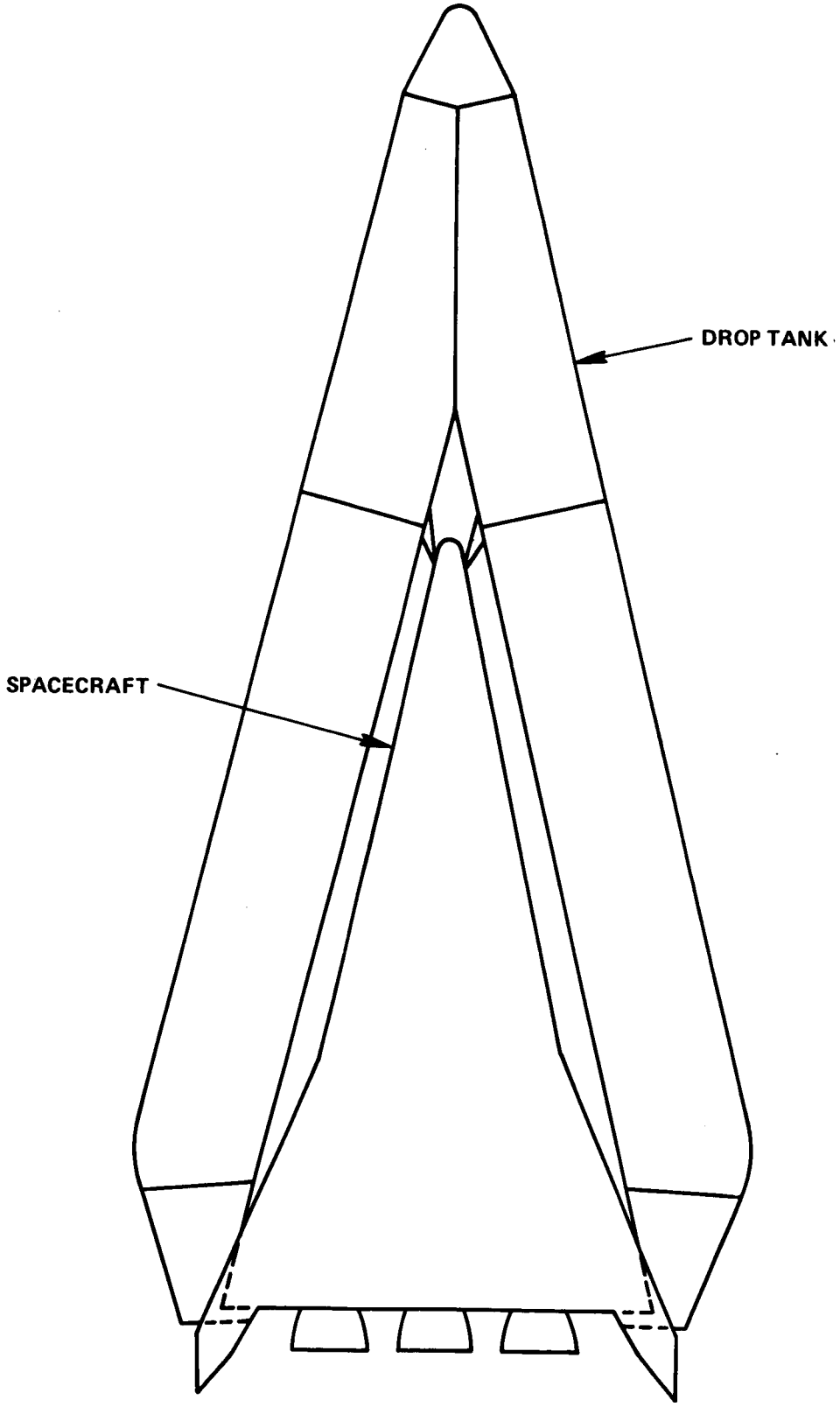
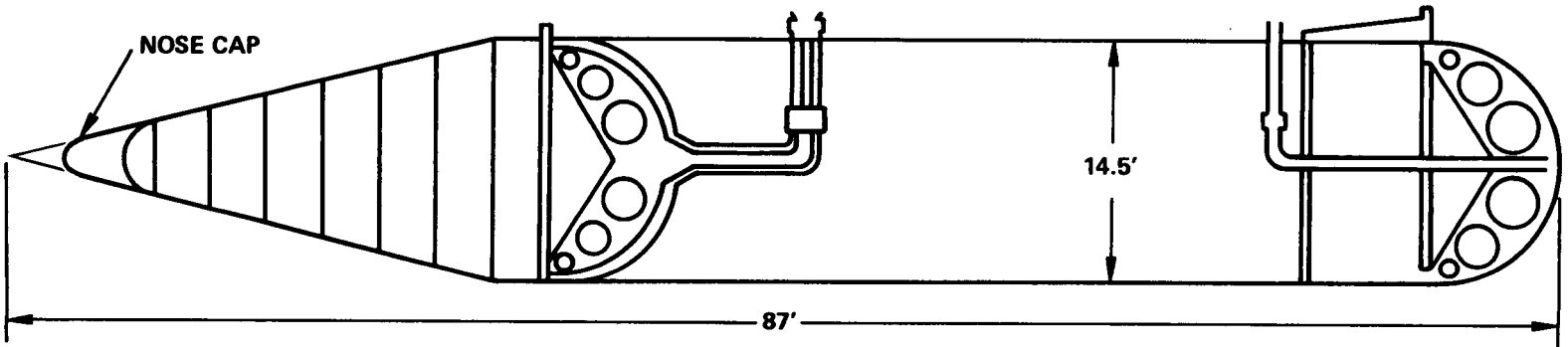


FIGURE 4. LOCKHEED "SPACE SHUTTLE"



STRUCTURAL CONCEPT – WELDED ASSEMBLY
NOSE CAP – SPUN STAINLESS STEEL
TANK SKIN – 7039 ALUM ALLOY (.063–.190t WITH NO CHEM MILLING)
RINGS – 7039 ALUM ALLOY FORGING

WEIGHTS – LB

STRUCTURE	9,985
INSULATION	2,245
EQUIPMENT	50
CONTINGENCY	400
TOTAL – DRY	12,680
RESIDUAL PROPELLANT	2,320
USABLE PROPELLANT	258,000
TOTAL	273,000

MIXTURE RATIO = 6
ULLAGE = 2%

	FT.^{3}
VOL. LOX TANK	3,200
VOL. LH_2 TANK	8,590
VOL. (TOTAL)	11,790

FIGURE 5. MODEL 176H TIP-TANK DESIGN SUMMARY

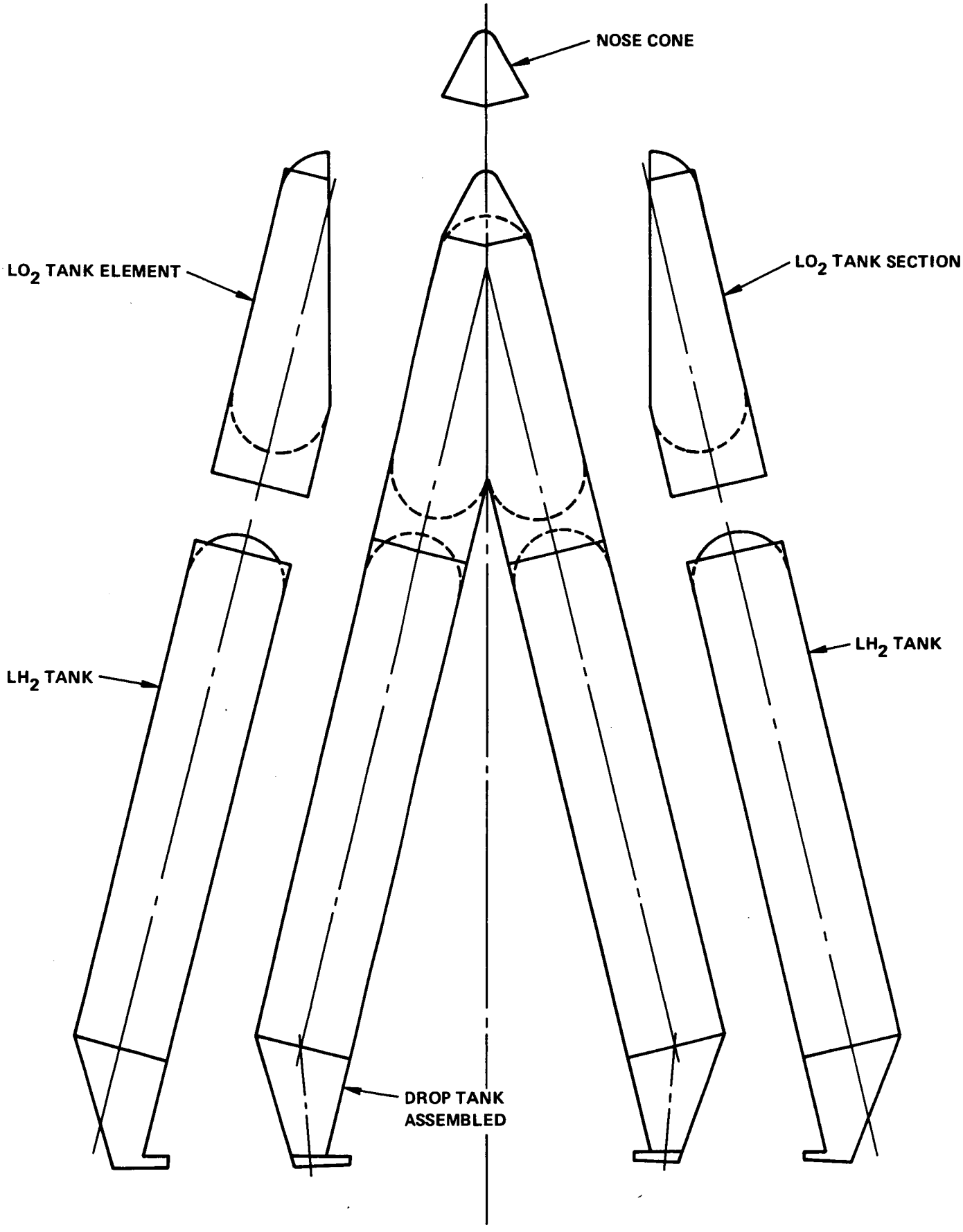
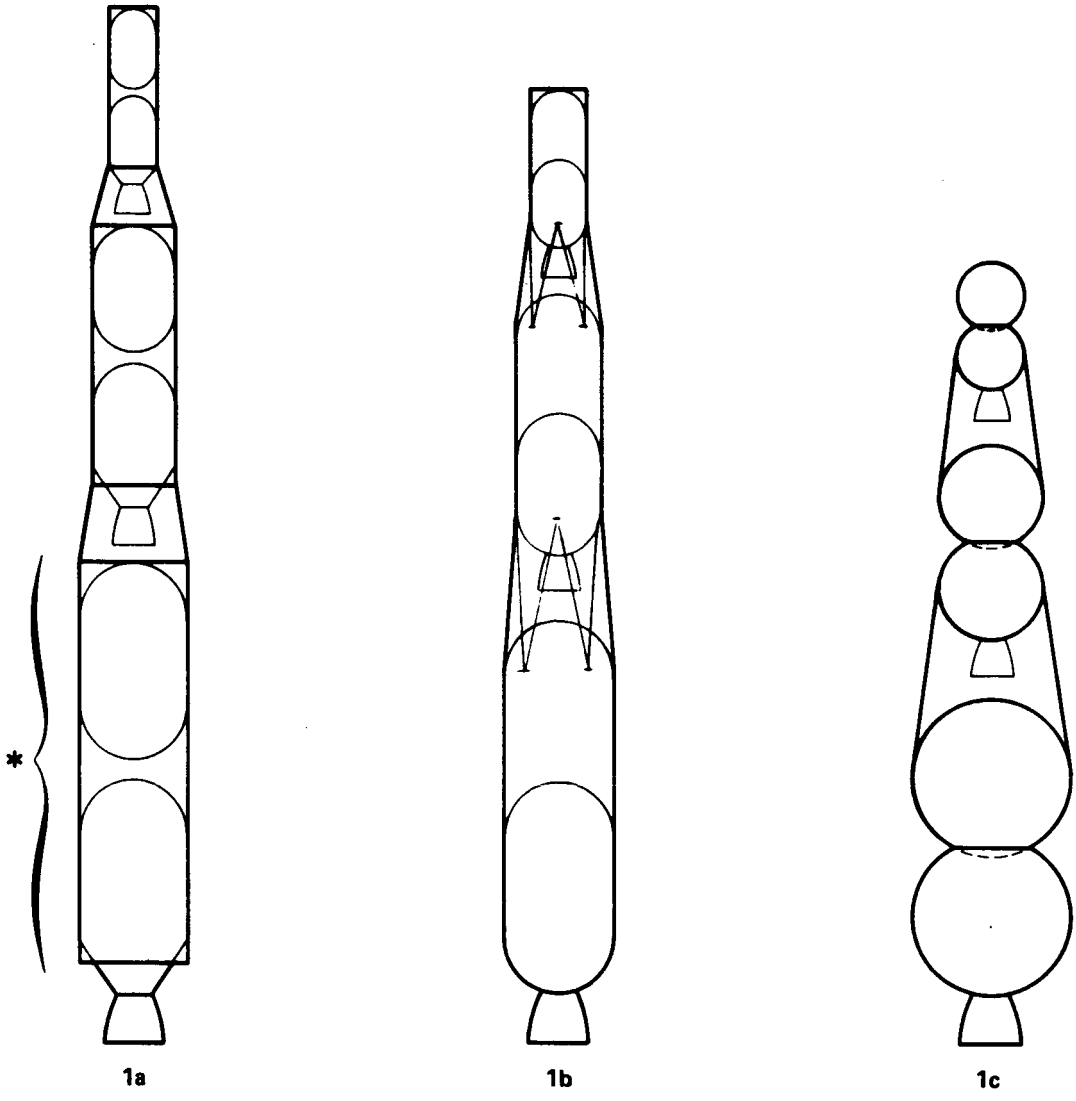


FIGURE 6. DROP TANK STRUCTURAL ELEMENTS



* STAGE SIMULATED FOR EXPERIMENTAL FABRICATION

FIGURE 7. LAUNCH VEHICLE CONFIGURATION

FIGURE 8

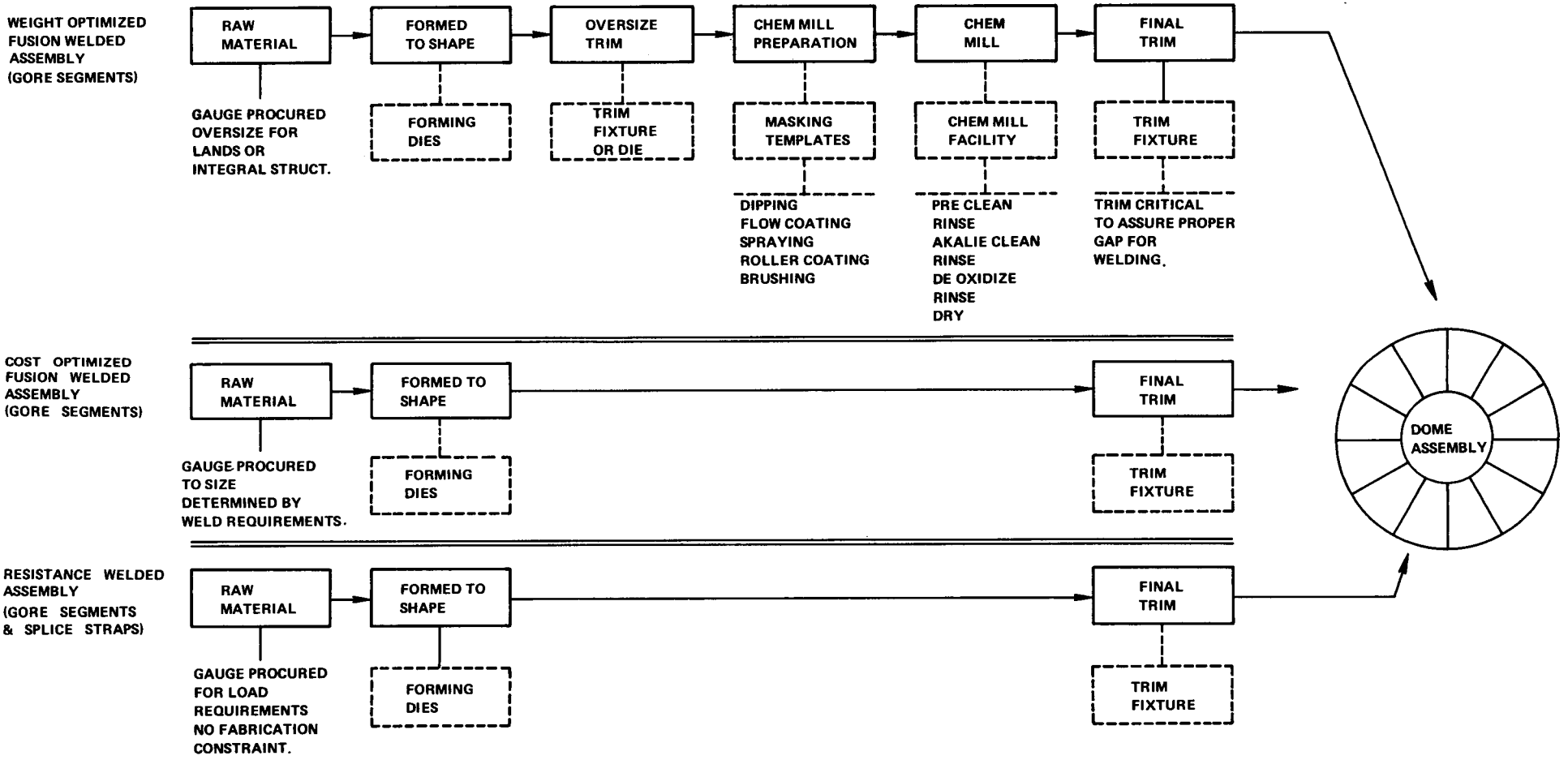
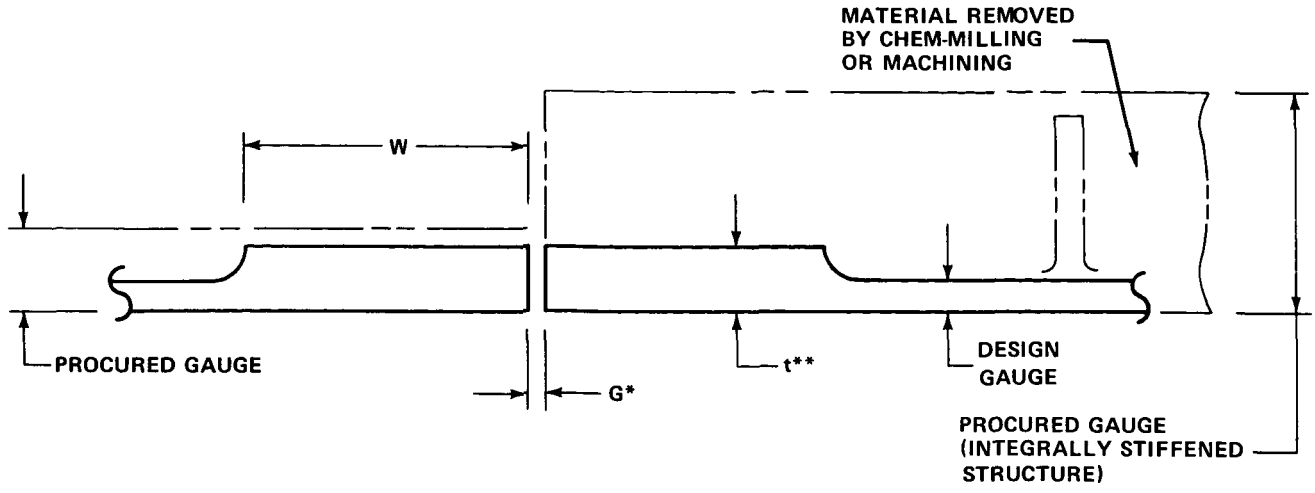
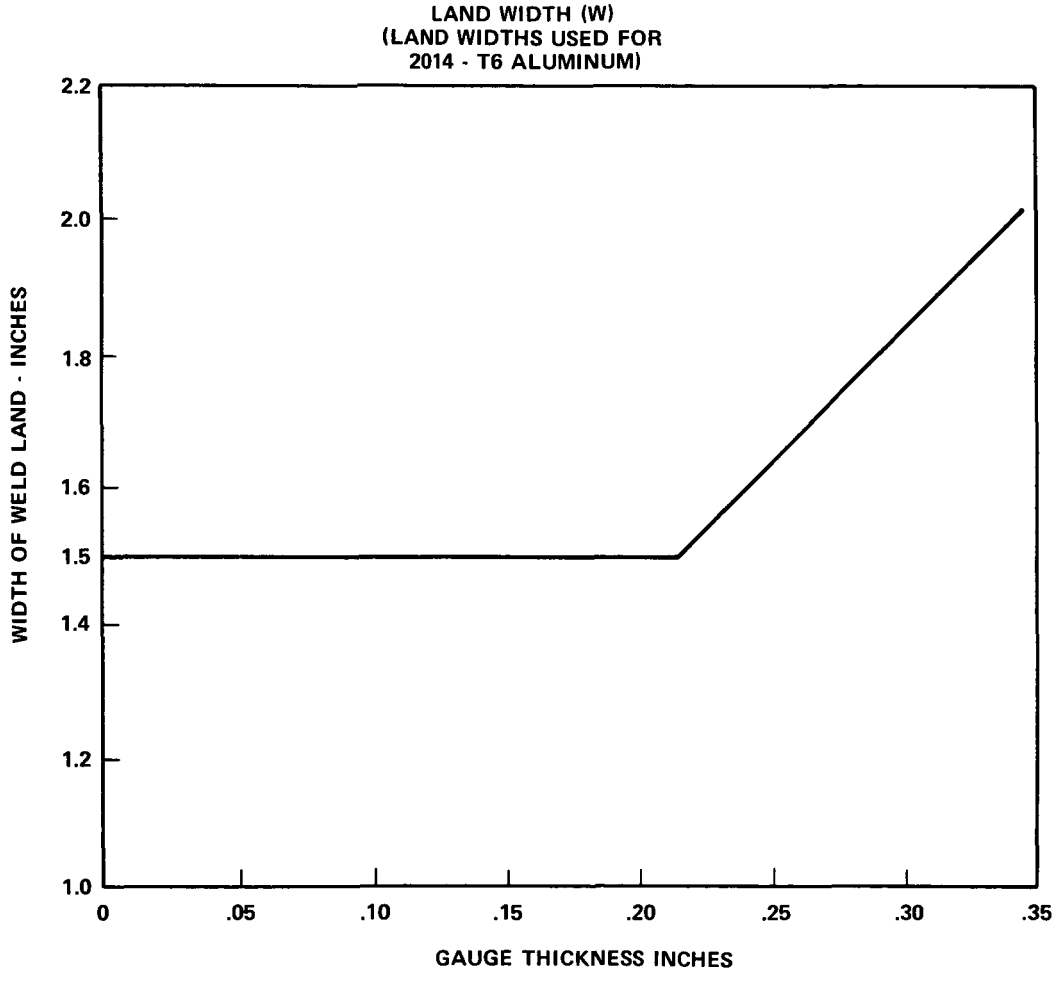


FIGURE 9. COMPARISON OF FABRICATION FUNCTIONS (DOME FABRICATION)





* THIS IS SET BY THE RESULTS OF TEST DATA FOR JOINT EFFICIENCY

** SIZED BY THE FOLLOWING:

- DECREASED MAT'L ALLOWABLE DUE TO TO WELDING (FOR 2014 & 2219 FT = 25000 PSI)
- MISMATCH BETWEEN SECTIONS TO BE JOINED
- FABRICATION DIMENSIONAL TOLERANCES
- REPAIR FACTOR (GENERALLY 15% OF DESIGN REQUIREMENT

FIGURE 10 – WELD LAND DESIGN & FABRICATION FEATURES

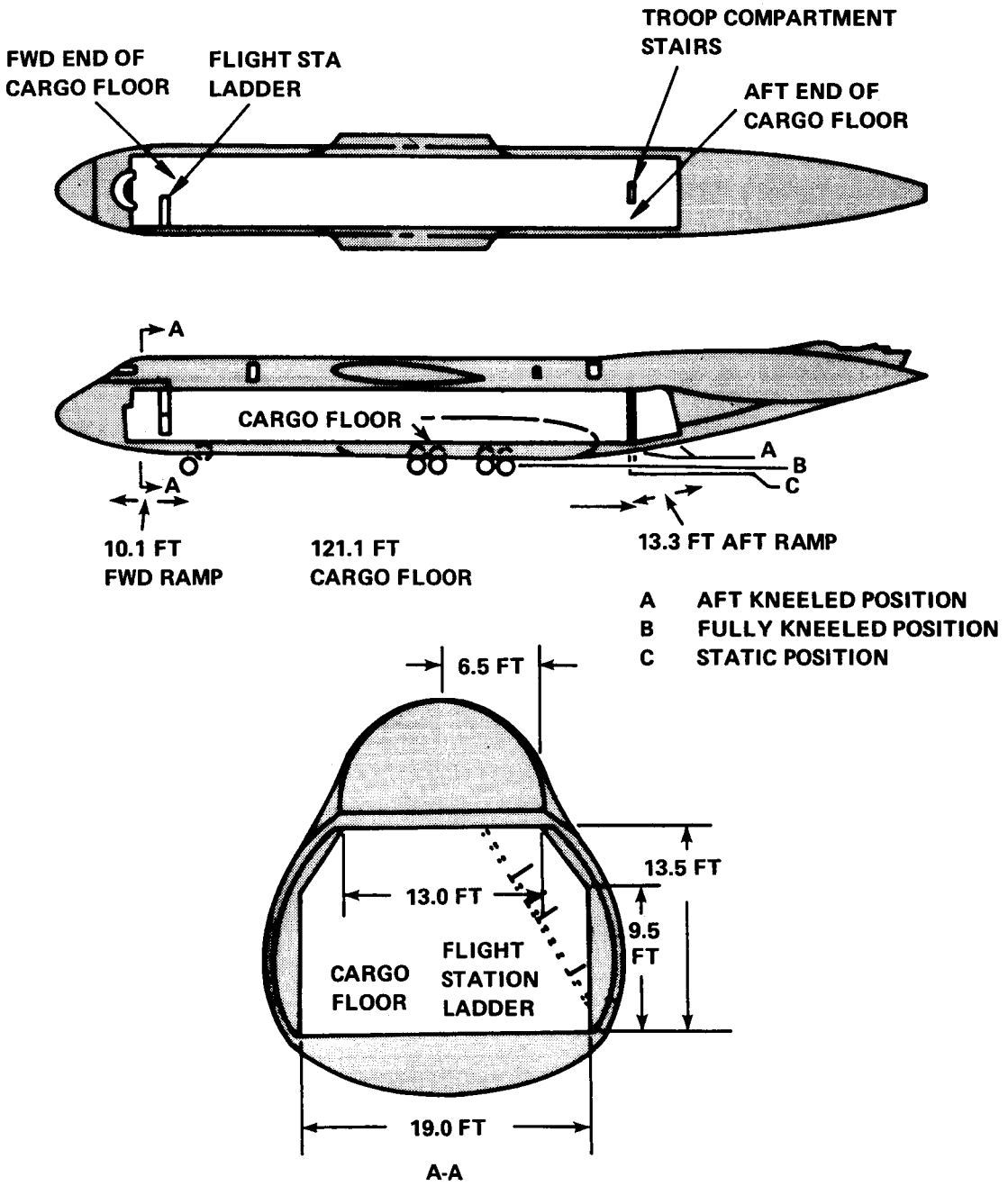


FIGURE 11. C-5A CARGO COMPARTMENT

TABLE 1. NORMALIZED BOOSTER COSTS LESS ENGINES

BOOSTER	INERT WEIGHT IN POUNDS		PROPELLANT WEIGHT IN POUNDS	NORMALIZED UNIT COST	PRODUCTION RATE #/YR
ATLAS	SUSTAINER TANKS	4390	268K	1.00	1
	BOOSTER STRUCT.	5233		.92	2
		9623		.87	3
				.84	4
				.81	5
				.79	6
THOR (LONG TANK)	4285		100K	1.00	1
				.72	2
				.61	3
				.54	4
				.50	5
				.47	6
				.44	7
				.42	8

TABLE 2. PRODUCTION RATE – COST COMPARISON (STRUCTURE)

VEHICLE TYPE	SYSTEM DESIGNATION	PRODUCTION RATE	COST/POUND
AUTOMOBILE	SO CALLED "BIG 3"	PRODUCED @ RATE OF ONE/MIN (ASSEMBLY LINE RATE)	<$1.00
AIRCRAFT TIP TANK	FUEL TIP TANK JETTISONABLE (F-4 AIRCRAFT)	50–55 PER DAY	~$11.00
AIRCRAFT STRUCTURE (MILITARY)	F-4	2.5–3.0 PER DAY	~$30.00
AIRCRAFT STRUCTURE (COMMERCIAL)	DC8, DC9	-----	$15.00–$18.00
BOOSTER TANKAGE	THOR	~10/YR	$41.00
BOOSTER TANKAGE	ATLAS	~10/YR	$27.00
BOOSTER TANKAGE	TITAN III C (1ST STAGE CORE)	~10/YR	$134.00
DROP TANK	STAR CLIPPER (LOCKHEED)	-----	$29.00 (ESTIMATED)
DROP TANK	TIP TANK (McDONNELL DOUGLAS)	-----	>$50.00 (ESTIMATED)
EXPENDABLE BOOSTER	"COLV" (BOEING)	~20/YR	1ST STAGE ~$2.50 (ESTIMATED) 2ND STAGE ~$16.00 (ESTIMATED)

TABLE 3. MATERIAL CONSIDERATIONS

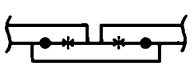
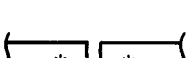
Material / Property	Condition	Test Temp. (°F)	F_{tu} (Ksi)	F_{ty} (Ksi)	Notched F_{tu} (Ksi)	Impact (ft-lb)	Notched Unnotched Ratio, F_{tu}	Fatigue Strength (Ksi)	Fract. Tough. K_{IC} (Ksi $\sqrt{in}$)	Weld Tensile F_{tu} (Ksi)	E (psi x 10^6)	Density σ (lb/in^3)	F_{tu}/σ x 10^6	Forming Capability *	Machining Capability *	Weldability *	Availability *	Temperature Service Range °F **	Sheet Cost ($/lb)
Aluminum 2219	-T87	RT	72	58	70	4.2	.97	20	27	51	10.3	.103	0.70	E	E	G	Mill order only	-423/300	1.00
		-320	90	69	84	4.2	.93	15-25	22	62	11.3	–	–						
		-423	98	75	96	4.2	.93	40	36	73	11.8	–	–						
2021	-T81	RT	66	56	61.5	–	.93	27	32.5	33	10.7	.103	0.64	E	E	G	Mill order only	-423/300	1.08
		-320	82	68	81.5	–	1.00	–	38.5	–	10.9	–	–						
		-423	90	73	–	–	–	–	40.0	–	12.0	–	–						
6061	-T62	RT	42	35	46	8.0	1.10	20	–	30	10.0	.098	0.43	E	E	E	Stock	-423/300	2.08
		-320	58	44	57	9.0	.98	38	–	44	10.5	–							
		-423	72	48	65	10.0	.91	–	–	59	10.9	–							
5083	-H39	RT	71	63	69	11.5	.97	16	–	42	10.2	.096	0.74	E	E	E	Stock	-423/300	2.02
		-320	87	75	82	11.0	.94	20	–	59	–	–							
		-423	101	79	91	–	.90	–	–	–	–	–							
7039	-T6	RT	67	60	72	6.0	1.07	18	72	54	10.1	.099	0.68	E	E	F-G	Mill order only	-423/300	2.50
		-320	85	71	78	5.0	.92	29	22	59	10.5	–							
		-423	98	76	83	4.5	.85	40	23	57	11.0	–							
Stainless Steel 301	3/4 H 40% Red.	RT	190	150	164	91.0	.87	70	–	144	26.0	.286	0.66	G-E	F-G	G	Stock	-423/1600	1.85
		-320	300	182	142	79.0	.47	110	–	204	28.0								
		-423	292	198	105	–	.36	95	–	148	30.0								
310	3/4 H 40% Red.	RT	154	138	170	72.0	1.10	–	–	66	28.0	.286	0.54	G-E	F-G	G	Stock	-423/1600	2.21
		-320	215	180	235	54.0	1.08	–	–	126	28.0	–							
		-423	278	200	276	45.0	1.00	–	–	148	29.0	–							
AM 355	CR & Temp.	RT	274	246	230	88	.85	–	–	220	25.5	.282	0.97	G-E	G	G	Stock	-423/1600	2.86
		-320	342	284	174	40	.51	–	–	298	26.0	–							
		-423	340	320	125		.37	–	–	140	26.5	–							
17-7 PH	TH1050	RT	190	184	160	5.0	.85	80	–	138	27.5	.276	0.69	G	G	G	Stock	-423/1600	2.33
		-320	250	234	154	3.0	.62	124	–	–	28.5	–							
		-423	263	256	109	–	.41	106	–	–	32.0	–							
Titanium Unalloyed	Annealed	RT	84	66	114	46.0	1.36	–	–	–	15.5	.163	0.52	F-G	F	G	Stock	-423/1200	11.00
		-320	148	134	158	17.0	1.06	–	–	–	16.5	–							
		-423	176	174	125	14.0	.71	–	–	–	17.0	–							
5A1-2.5 SN ELI	Annealed	RT	120	115	160	26.0	1.33	75	118	120	16.0	.162	0.74	F-G	F	G	Stock	-423/1200	11.00
		-320	195	180	220	8.5	1.13	120	61	194	16.5	–							
		-423	245	230	208	6.5	.85	130	52	234	17.0	–							
6A1-4V ELI	Annealed	RT	142	130	156	16.5	1.10	42	–	142	15.5	.160	0.79	F-G	F	G	Stock	-423/1200	11.00
		-320	215	206	190	11.0	.88	72	–	216	17.0	–							
		-423	254	245	184	13.0	.73	76	37.5	276	18.0	–							
Steel HY-140		RT	143	138	–	90-100	–	–	>250	–	~30.0	~.3	~1.0	G	G	G	Mill order only	-100/1000	2.00
		-320	192	189	–	7-15	–	–	40	–		–							
		-423	–	–	–	–	–	–	–	–	–	–							
18% Ni Managing (250)	S. T. & Aged	RT	250	172	273	23.0	1.09	–	84	220	25.5	.289	0.87	G	G	G-E	Stock	-423/1200	2.50
		-320	315	244	284	20.0	0.90	–	97	302	27.5	–							
		-423	366	270	102	16.0	0.38	–	74	292	28.0	–							
Nickel Base Rene' 41	S. T. & Aged	RT	198	136	180	15.0	0.91	–	142	153	28.5	.298	0.66	F-G	F-G	G	Stock	-423/1650	9.18
		-320	223	178	186	11.0	0.83	–	139	195	30.0	–							
		-423	238	196	196	12.0	0.83	–	130	205	30.5	–							
Inconel 718	Annealed & Aged	RT	194	156	197	16.0	1.01	70	119	112	29.8	.297	0.65	F-G	F-G	G	Stock	-423/1650	3.57
		-320	232	184	231	13.5	1.00	62	143	145	31.3	–							
		-423	278	204	259	–	0.93	95	152	146	29.9								

*E = Excellent
G = Good
F = Fair, but no real problems

"Stock" may be 2-12 weeks delivery.

** Upper end of range for 300 seconds duration, maximum

TABLE 4. JOINTING METHOD COMPARISON

JOINT TYPE	JOINING METHOD	STRUCTURE DESIGN		GAUGE (t) DETERMINATION	RAW MATERIAL		SPLICE MEMBER	GAP REQUIREMENT	FABRICATION COMPLEXITY	REMARKS
		PRESSURE STABILIZED	STATICALLY STABLE		TO SIZE	OVER SIZE				
	FUSION WELD	√	√	DETERMINED BY MATERIAL WELD ALLOWABLE, MISMATCH, REPAIR	√		NO	CONTROLLED BY GAUGES TO BE JOINED	LOW	USED WITH (COLV) CONCEPT (COST OPTIMIZED WITH WEIGHT SECONDARY FACTOR)
	FUSION WELD	√	√	DETERMINED BY MATERIAL WELD ALLOWABLE MISMATCH, & REPAIR (2)		√	NO	CONTROLLED BY GAUGES TO BE JOINED	HIGH (REQUIRES MACHINING & CHEM MILLING FOR MATERIAL REDUCTION	USED FOR THOR, TITAN, & SATURN BOOSTERS, TANKAGE FOR EACH OF THESE SYSTEMS CAN BE HANDLED WITHOUT TANKAGE PRESSURIZATION – TO BE USED FOR TIP TANK CONCEPT
	RESISTANCE WELD (SEAM TYPE)	√		LOAD DEPENDENT	√		NO	NONE	LOW	USED FOR ATLAS & CENTAUR – REQUIRES CONSTANT PRESSURIZATION TO SUPPORT COMPLETED TANK STRUCTURE
	RESISTANCE WELD (COMBINED SEAM & SPOT)	√		LOAD DEPENDENT	√		YES	GAP CAN BE VARIABLE	MODERATE	USED WITH STAGE AND HALF LO_2 TANK. WILL REQUIRE PRESSURIZATION FOR TANKAGE SUPPORT
	GLUE WELD (COMBINED SPOT & EPOXY BOND) (1)	√		LOAD DEPENDENT	√		YES	GAP CAN BE VARIABLE	MODERATE	USED WITH STAGE AND HALF LH_2 TANK – WILL REQUIRE PRESSURIZATION FOR TANKAGE SUPPORT. THIS METHOD, USING EPOXY, IS NOT COMPATIBLE WITH LO_2 AT PRESENT.

(1) EMPLOYS THE USE OF ALUMINUM FILLED HIGH STRENGTH EPOXY FOR SEALING & SPOT WELD FOR STRUCTURAL REDUNDANCY & FABRICATION ASSIST
(2) SEE WELD LAND DISCUSSION

TABLE 5

AIRFRAME COMPLEXITY FACTORS

CONSTRUCTION TYPE	MATERIAL TYPE		
	ALUMINUM	STAINLESS STEEL	TITANIUM
MONOCOQUE	0.6	1.5	1.8
SKIN, RING & STRINGER	1.0	1.8	3.0
HONEY COMB SANDWICH (BONDED)	1.6	2.7	3.2
MILLED INTEGRALLY STIFFENED	1.8	2.2	4.5
CORRUGATION STIFFENED SKIN	1.3	2.2	3.9
SPACE FRAME (TRUS)	0.7	0.9	1.5

NOTE: UNITY FOR THIS TABULATION WAS SKIN, RING & STRINGER STRUCTURE

BELLCOMM, INC.

Subject: Assessment of Expendable Tankage
for Low Cost Transportation Systems
Case 105-3

From: A. S. Kiersarsky

DISTRIBUTION LIST

NASA Headquarters

J. R. Burke/MTV
L. E. Day/MAT
C. J. Donlan/MD-T
L. K. Fero/MLV
E. W. Hall/MTG
D. R. Lord/MTD
J. L. Roberts/MTV
A. D. Schnyer/MTV
W. A. Summerfelt/H-1
A. O. Tischler/RP
W. W. Wilcox/RPX

MSFC

W. G. Huber/R-AS-S-DIR
W. R. Lucas/R-P&VE-DIR
L. T. Spears/R-AS-S

MSC

J. Hodge/HA

ARC

H. Hornby/MO
L. Roberts/M

KSC

G. M. Preston/DE

Bellcomm, Inc.

G. M. Anderson
A. P. Boysen
D. R. Hagner
W. W. Hough
B. T. Howard
J. Kranton
J. Z. Menard
I. M. Ross
J. W. Timko
R. L. Wagner
J. E. Waldo
M. P. Wilson
All Members Division 101
Central Files
Department 1024 File
Library